REMARKS/ARGUMENTS

Re-examination and favorable reconsideration in light of the above amendments and the following comments are respectfully requested.

Claims 1 -11 are pending in the application. Currently, claims 1 - 10 stand rejected and claim 11 stands withdrawn from consideration as being directed to a non-elected invention.

The sole rejection made by the Examiner is a rejection of claims 1 - 10 under 35 U.S.C. 112, first paragraph as failing to comply with the enablement requirement.

The foregoing rejection is traversed by the instant response.

The present invention relates to a reduced gain thrust control valve for use in a rocket engine. The control valve comprises a housing having a fluid inlet, which has at least one metering element formed therein. The at least one metering element comprises a first means for producing improved control stability, second means for controlling thrust during a start transient engine phase, and third means for accommodating a retainer. The valve further has a piston and cylinder unit for controlling a fluid output of the control valve.

With respect to the rejection under 35 U.S.C. 112, first paragraph, it seems that the Examiner is not grasping the environment in which the claimed control valve is used. In

rocket engines, there are fluid lines for fluids which bypass a particular turbine. Attached hereto for the Examiner's benefit are the articles "AE6450 Lecture #7 Bi-Propellant Liquid Rocket Engines" and "Throttling Dynamic Response of LH2 Rocket Engine for Vertical Landing Rocket Vehicle." With respect to the former article, the Examiner's attention is directed to the figure on Page 15 which shows the use of a turbine bypass valve (TBV) in connection with a rocket engine. With respect to the latter article, the Examiner's attention is directed to FIG. 3 which shows a thrust control valve which is used in a line that bypasses a turbine. As can be seen from both these figures, the valves have a single input and a single output - just like the valve described in the instant application.

There can be no question that this is how the valve of the present invention is intended to be used. The last sentence of paragraph 0003 clearly says that one of the problems being solved by Applicants' valve are the inconsistent results from hardware changes intended to adjust the fixed turbine bypass flow rate. Further, in paragraph 0021, it is clearly stated that when the valve is opened, it bypasses flow (power) around the turbine (not shown). To do this, the valve must be associated with a turbine bypass line.

There is no question that a fully operative control valve has been described in the specification of the instant

application. The Examiner raises no question on the operation of the valve. The Examiner has provided no reason why one of ordinary skill in the art presented with the instant disclosure could not make and use the claimed valve. As for the question raised by the Examiner about the bypass, it is the outlet of the valve which is the bypass flow. The metering element(s) determine the bypass flow rate exiting the valve through the single outlet. It is submitted that one of ordinary skill in the art could make and use the valve of the present invention without any undue experimentation.

It should also be noted that the claims in this application are directed solely to the construction of the valve and not to the manner in which the valve is being used. The use of language such as "a fixed turbine bypass portion" merely describes a structural feature of the valve. Since Applicants can be their own lexicographer and are not using the term in an inappropriate manner, this language is proper and would be readily understood by one of ordinary skill in the art. However, if the Examiner desires other language, the Examiner should feel free to suggest same.

For the foregoing reasons, the rejection of record should be withdrawn.

The instant application is in condition for allowance. Such allowance is respectfully solicited.

A notice of appeal is appended hereto in the event the Examiner maintains the rejection of record.

Should the Examiner believe an additional amendment is needed to place the case in condition for allowance, he is hereby invited to contact Applicants' attorney at the telephone number listed below.

The Director is hereby authorized to charge the Notice of Appeal fee to Deposit Account No. 21 - 0279. Should the Director determine that an additional fee is due, he is hereby authorized to charge said fee to said Deposit Account.

Respectfully submitted,

Tim Joseph Avampato, et al.

By ______________________
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Date: August 1, 2006

I, Karen M. Gill, hereby certify that this correspondence is being deposited with the United States Postal Service with sufficient postage as first class mail in an envelope addressed to: "Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313" on **August 1, 2006**.

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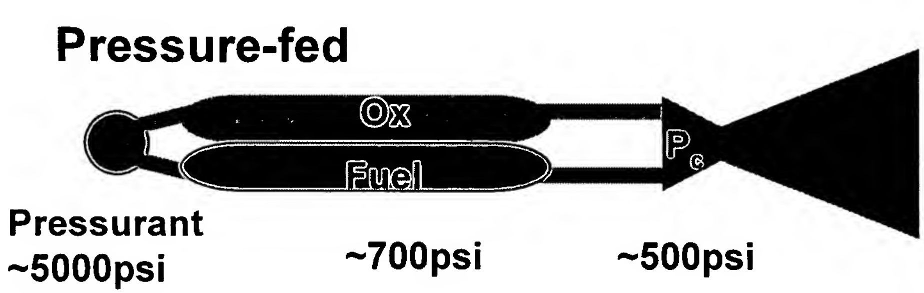
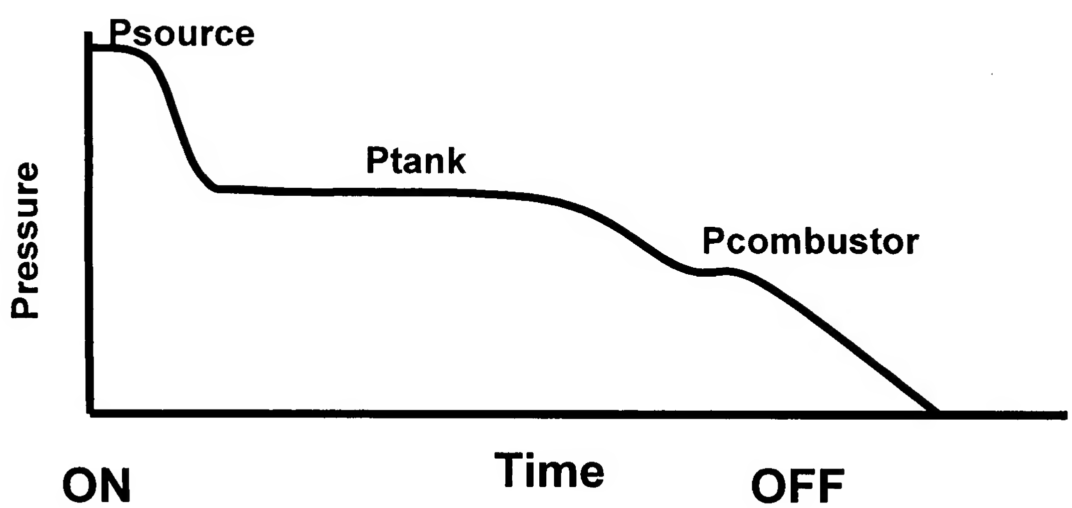
AE6450 Lecture #7
Bi-propellant Liquid Rocket Engines

Pressure-Fed vs. Pump-fed Systems

Liquid Rocket Engines fall into two major categories depending on how propellants are supplied to the engine.





A separate, high pressure inert gas (N_2 or He) is used to provide the liquid to the combustion chamber.

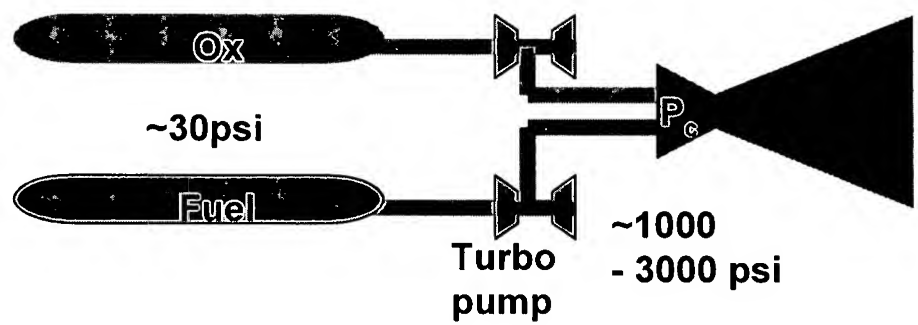
- creates a simpler engine, lower cost

- high pressure tanks and lines add system weight

- lower P_c = lower I_{sp}

As a general rule, pressure-fed systems are not competitive with pump-fed systems for large scale engines.

Pump-fed Systems



- higher P_c, so higher I_{sp}
- lower tank pressure and weights
- more complexity and cost

From this point forward, we will concentrate on pump-fed engines.

How do we drive the turbines for the turbopumps?

Engine Cycles

Open (drive gases do not go through throat)

Gas Generator
- some propellant is diverted into a smaller chamber to generate drive gases.

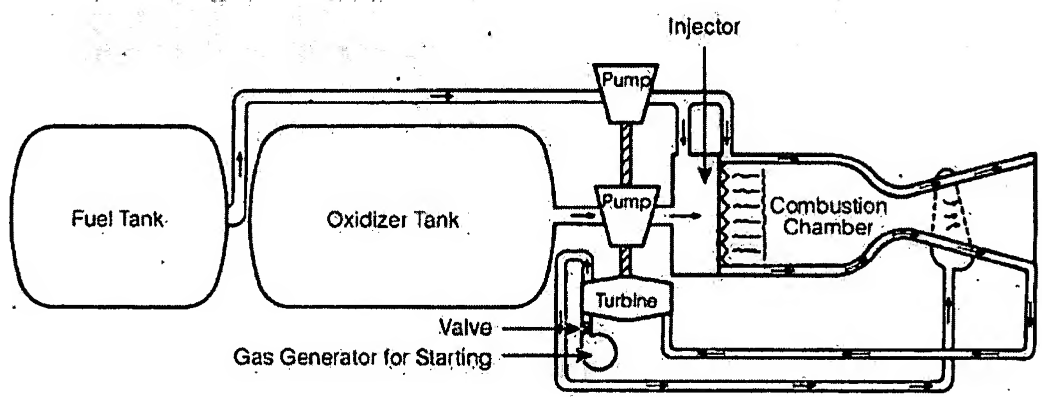
Example
F-1
J-2

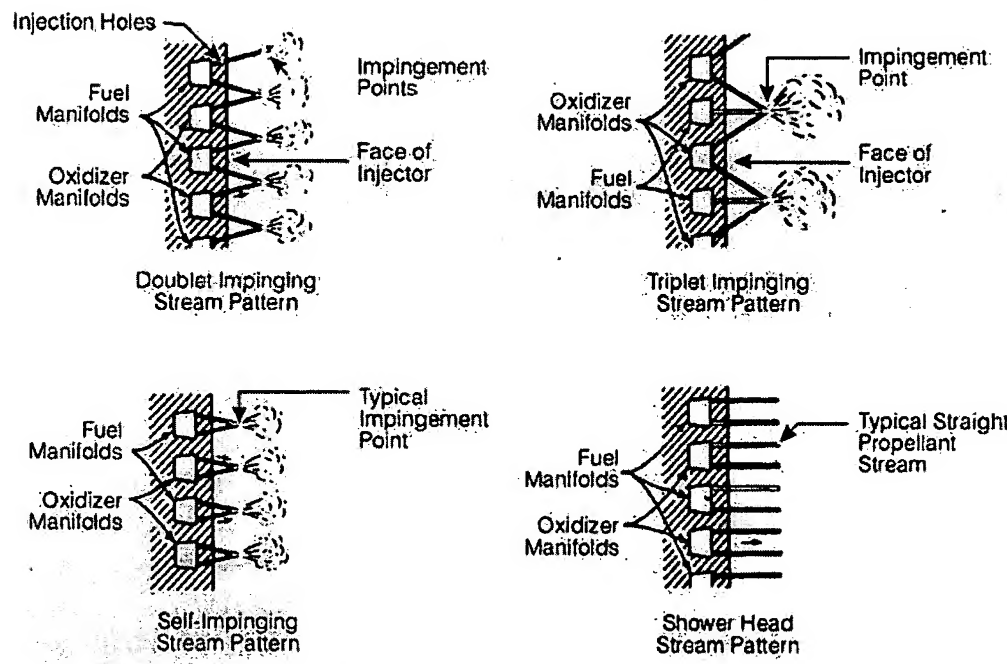
Tap-off cycle
- some gas is bled directly from the combustion chamber to drive turbines.

Example
J2-S

As a general rule, open cycles are slightly lower performance (2%-5% lower I_{sp}) than closed cycles.

Top, liquid-fuel rocket engine showing location of injector. Bottom, representative types of injector. (Cornelisse et al., p. 209; Sutton, p. 208)





http://history.nasa.gov/SP-4221/p19.htm

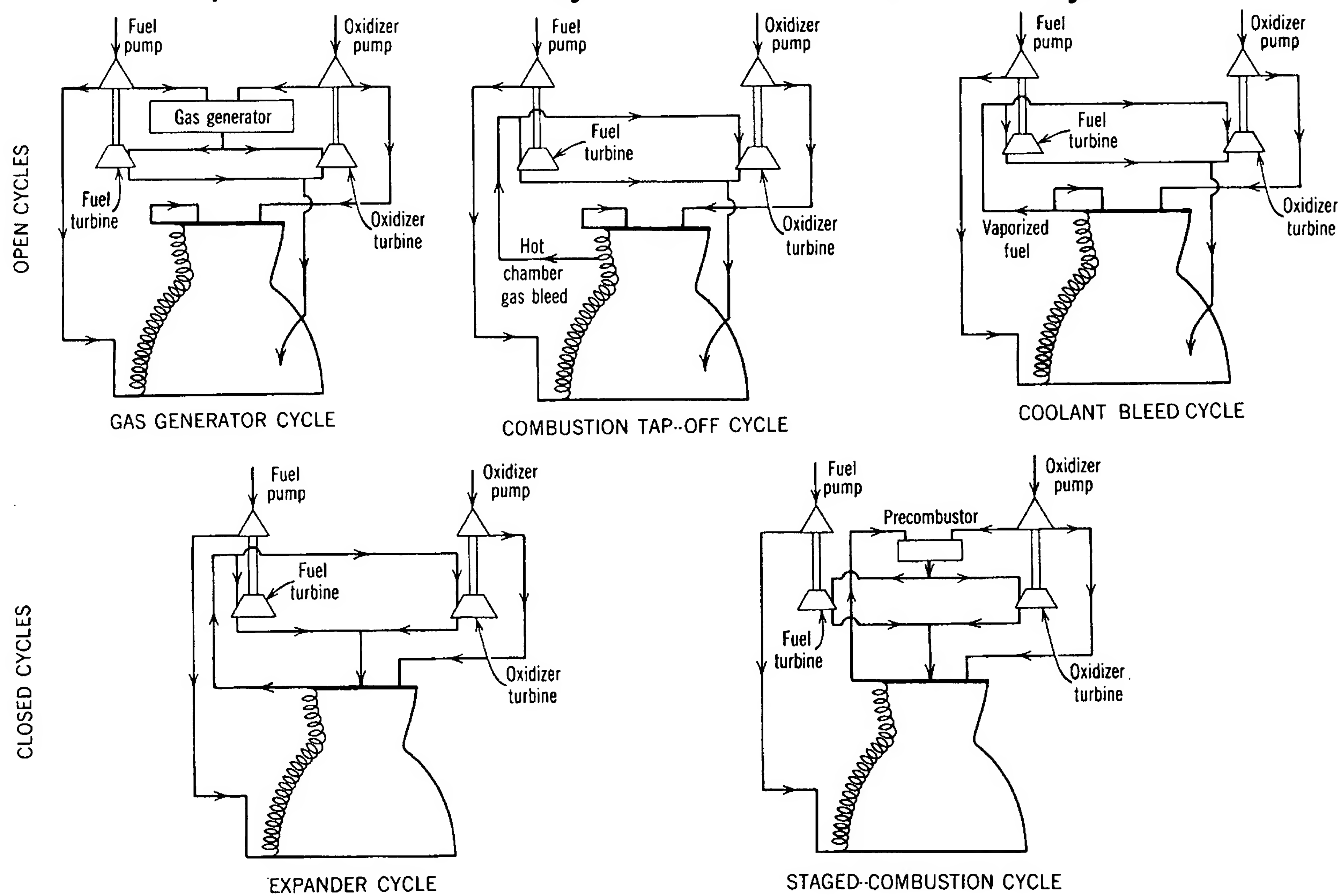
Open or Closed Cycle Feed Mechanisms

- Open Cycle – Turbine exhaust is discharged into engine nozzle or out separate nozzle

- Closed Cycle – Turbine exhaust is injected into combustion chamber
  - Higher Isp (1-5%) because turbine exhaust goes through full pressure ratio of engine
  - Pump turbine must operate at a higher pressure than an open cycle turbo-pump

Courtesy Dr. Dianne Deturris, CalPoly U.

Open and Closed Cycle Feed Mechanism Layouts



Courtesy Dr. Dianne Deturris, CalPoly U.

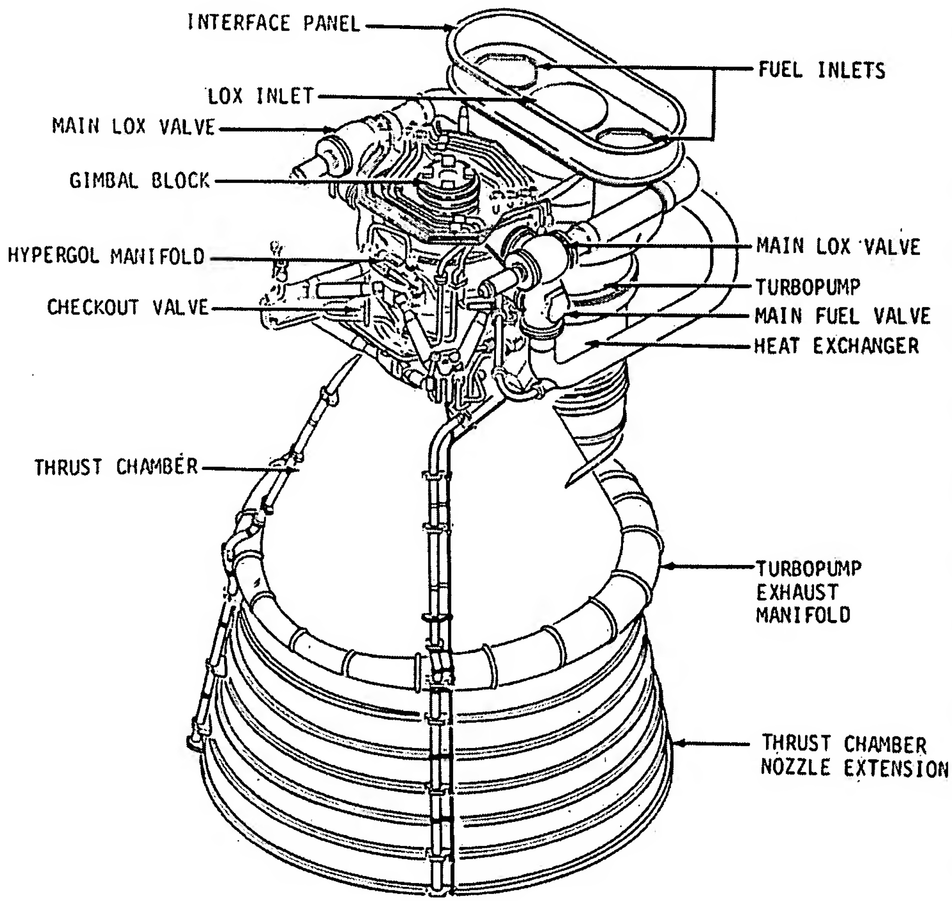
Closed Cycle – drive gas propellants also go through throat (no waste of propellants)

Expander cycle
- fuel is vaporized in cooling jackets and used to drive the turbines. Example:

Pratt & Whitney RL-10 rocket engine, the first to use liquid hydrogen. Thrust, 67 kN at altitude; exhaust velocity, 4245 m/s; exit, diameter, about 1 m. First engine run. July 1959, two of these engines powered the Centaur stage.

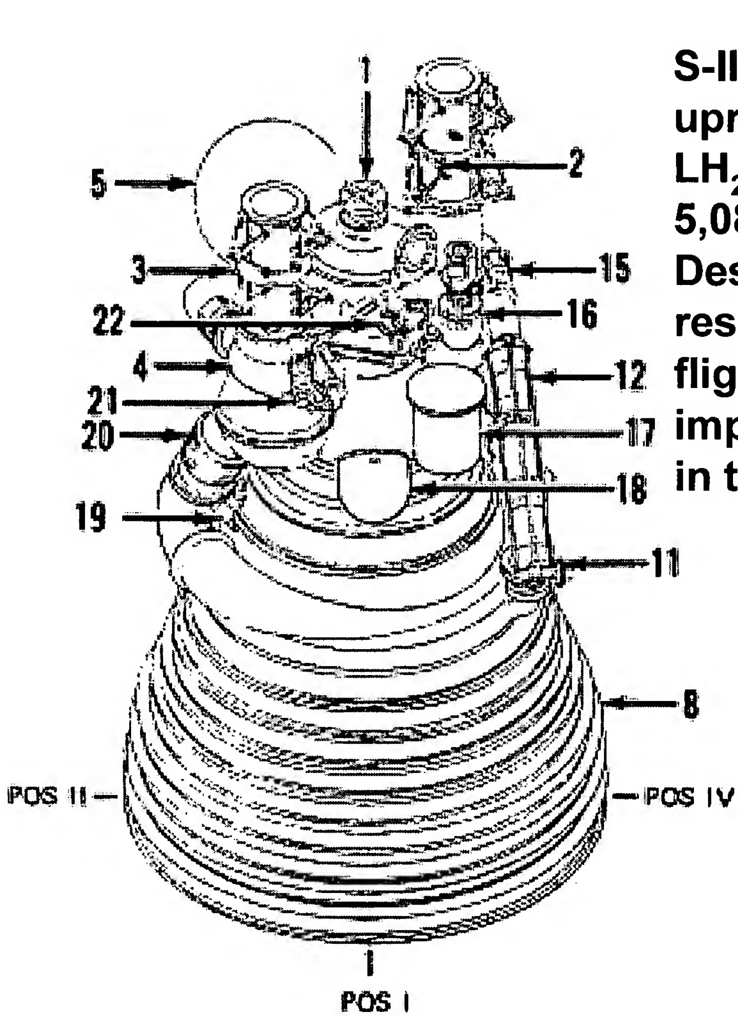
http://www.hq.nasa.gov/office/pao/History/SP-4404/ch10-7.htm

F-1 Engine

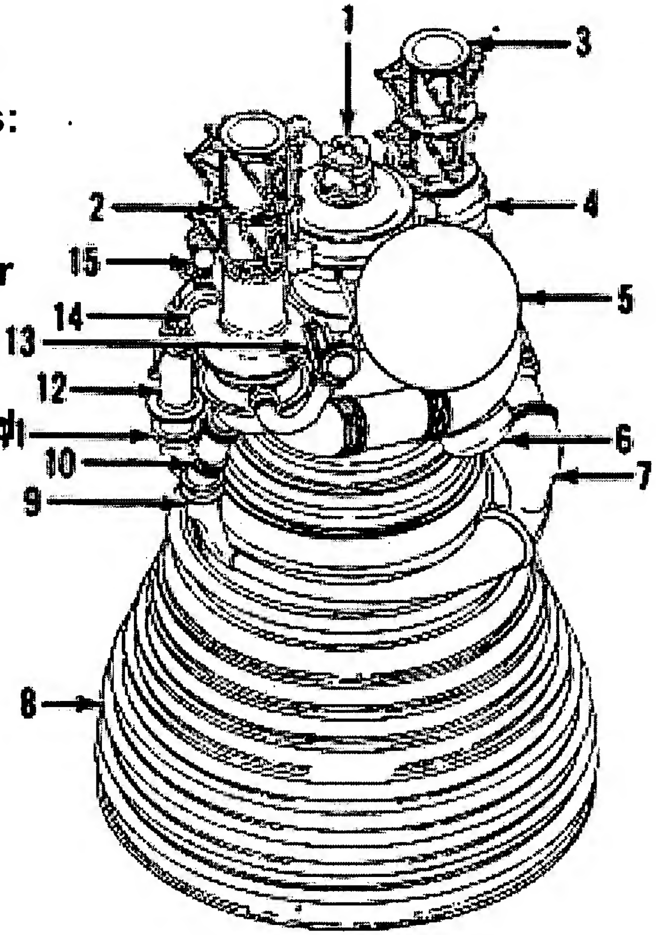


Large combustion chamber and bell -injector plate at the top - RP-1 and LOX injected at high pressure. LOX dome above injector also transmits the thrust from the engine to the rocket's structure. Single-shaft turbopump mounted beside combustion chamber. Turbine at bottom, driven by exhaust gas from fuel-rich gas generator. Turbine exhaust passes through heat exchanger, to wrap-around exhaust manifold and into nozzle periphery - to cool and protect the nozzle extension from the far hotter core flow. Fuel pump above turbine, on the same shaft. Two inlets from fuel tank and two valved outlets to injector plate and gas generator. Fuel & RJ-1 ramjet fuel also used as lubricant and hydraulic working fluid. LOX pump at top of turbopump shaft with single, large inlet in-line with the turboshaft axis. Two outlet lines with valves feed the injector plate and gas generator. Interior lining of combustion chamber and engine bell – fuel feed pipework. Igniter with cartridge of hypergolic triethylboron with 10-15% triethylaluminium, with burst diaphragms at high pressure fuel circuit, with its int in the combustion chamber. [9]

history.nasa.gov/ap08fj/ 01launch ascent.



S-II stage: 5 uprated J-2s: LH_2- LOX 5,087 kN. Designed for restarting in flight but implemented in the S-IVB

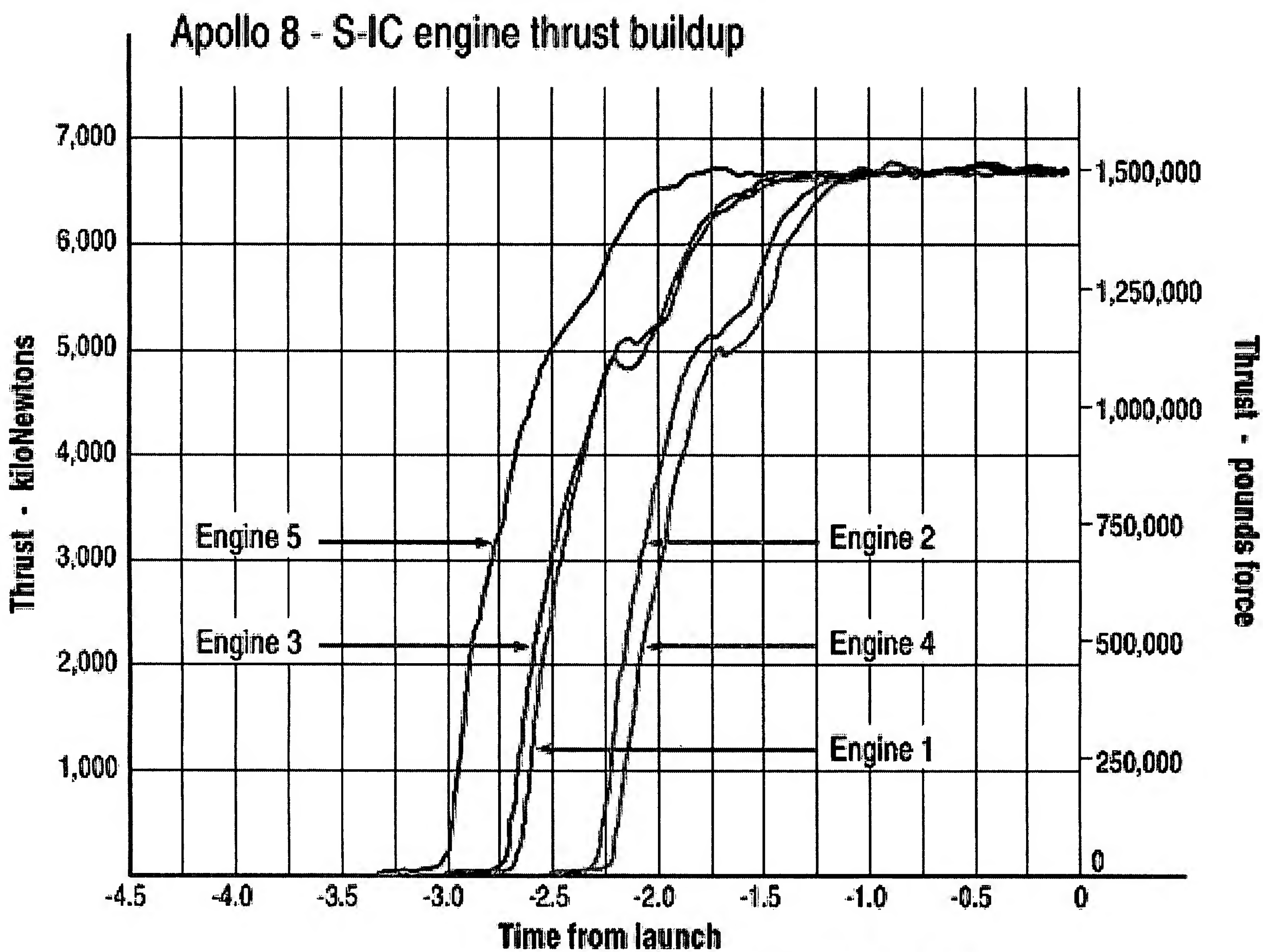


VIEW ROTATED 180°

LEGEND

1. GIMBAL
2. FUEL INLET DUCT
3. OXIDIZER INLET DUCT
4. OXIDIZER TURBOPUMP
5. START TANK
6. AUXILIARY FLIGHT INSTRUMENTATION PACKAGE
7. EXHAUST MANIFOLD
8. THRUST CHAMBER
9. OXIDIZER TURBINE BYPASS VALVE
10. TURBINE BYPASS DUCT
11. MAIN FUEL VALVE
12. HIGH PRESSURE FUEL DUCT
13. START TANK DISCHARGE VALVE
14. FUEL TURBOPUMP
15. FUEL BLEED VALVE
16. GAS GENERATOR
17. ELECTRICAL CONTROL PACKAGE
18. PRIMARY FLIGHT INSTR. PACKAGE
19. ANTI-FLOOD CHECK VALVE
20. HEAT EXCHANGER
21. MIXTURE RATIO CONTROL VALVE
22. PNEUMATIC CONTROL PACKAGE

history.nasa.gov/ap08fj/ 01launch_ascent.htm

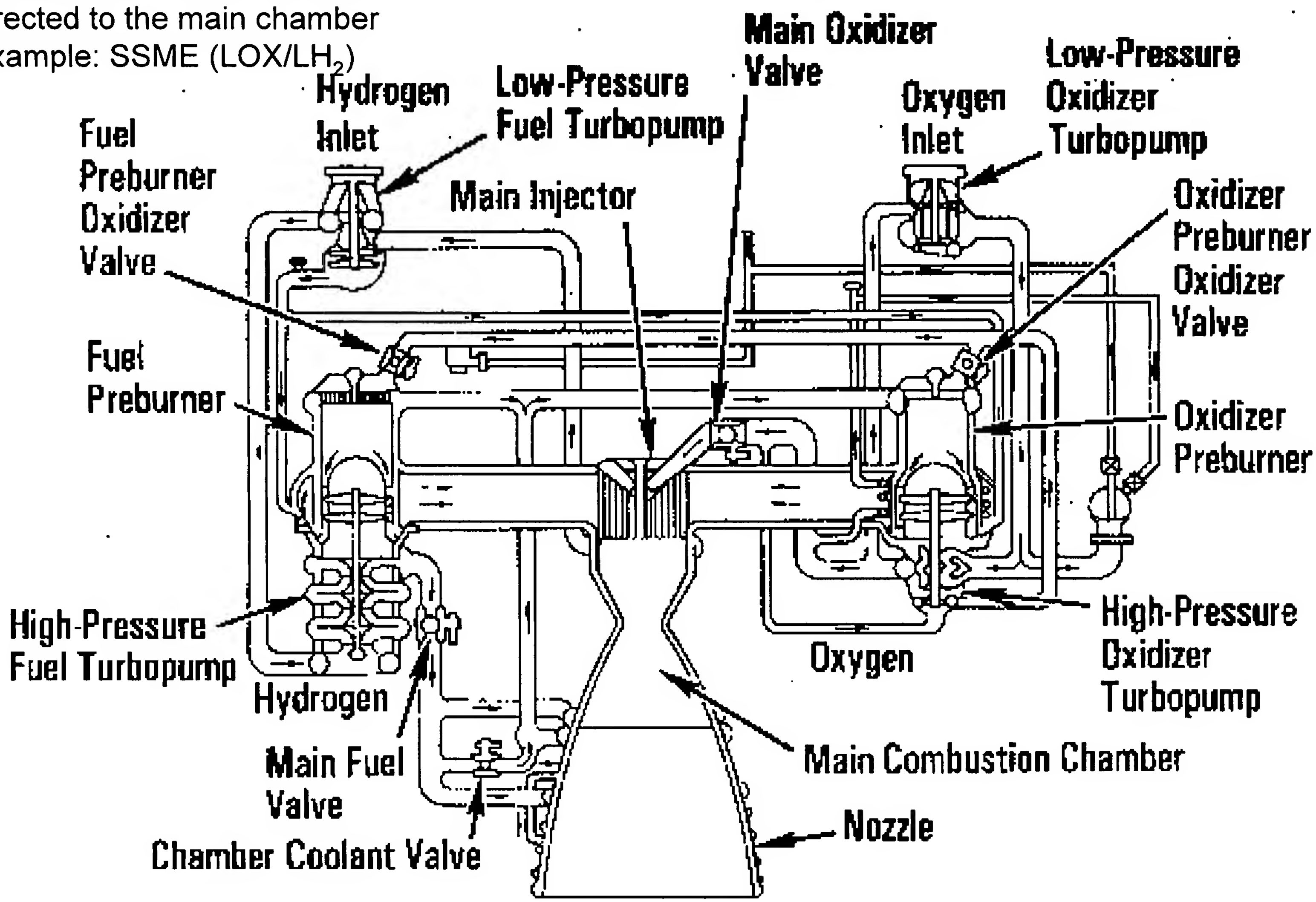


history.nasa.gov/ap08fj/ 01launch_ascent.htm

Staged-Combustion

A pre-burner is used to vaporize all of the fuel – the residual fuel-rich gas drives the turbine and then is directed to the main chamber

Example: SSME (LOX/LH_2)

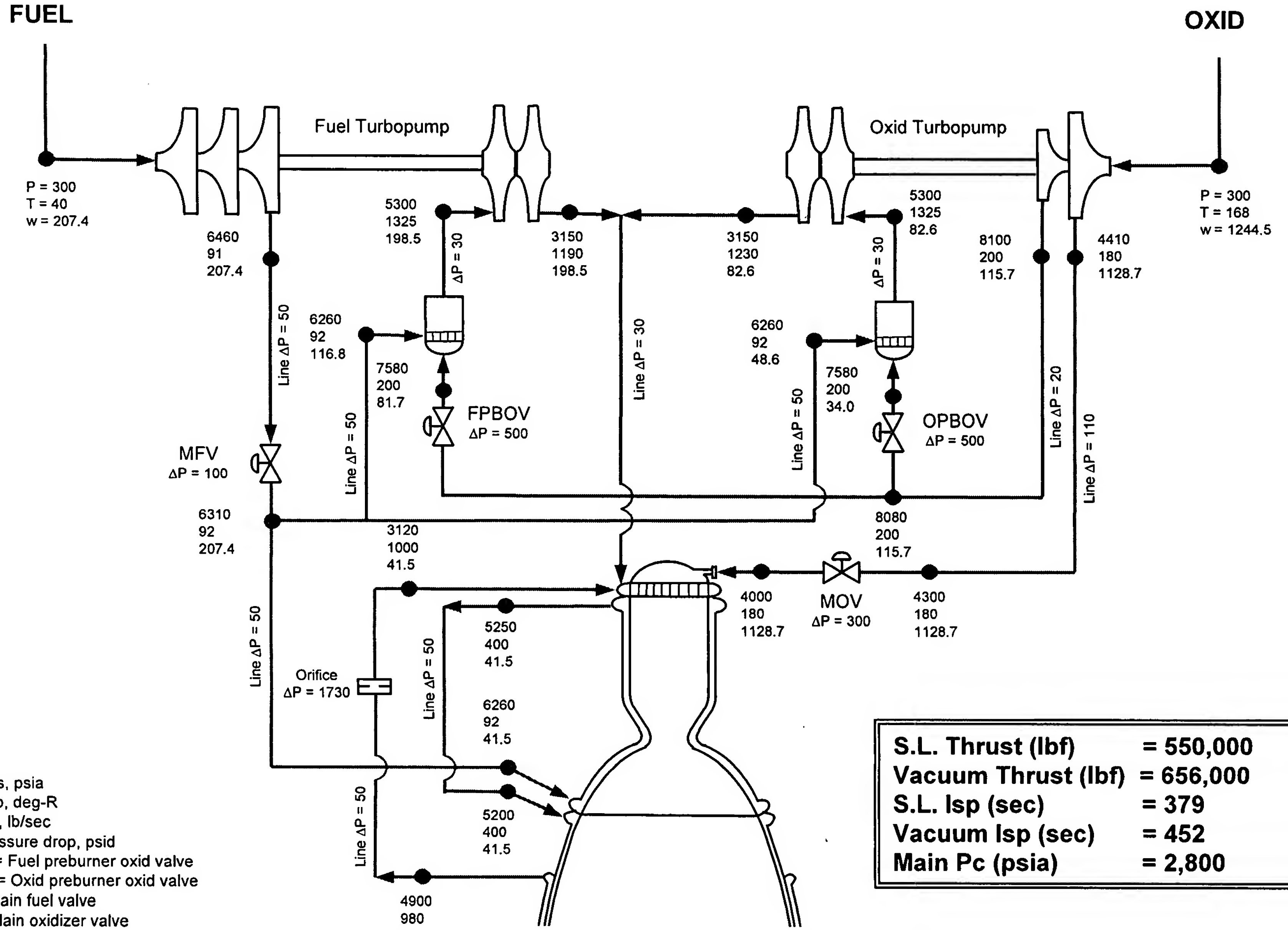


Main Engine Flow

Sample Engine Balances

Courtesy Dr. Dianne Deturris, CalPoly U. &
Boeing Co., Rocketdyne Division

Sample Staged-Comb. Cycle Engine Balance

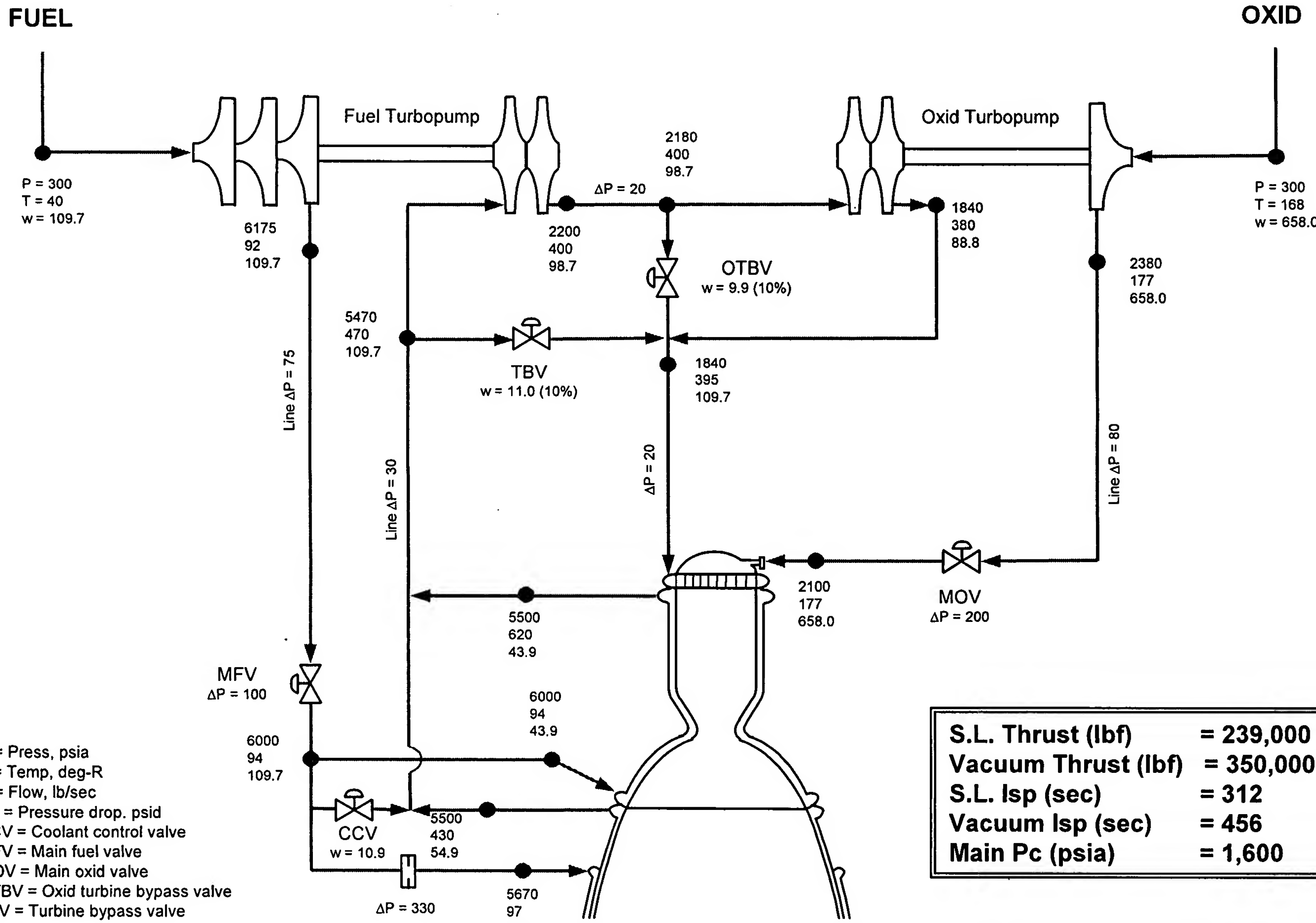


P = Press, psia
T = Temp, deg-R
w = Flow, lb/sec
ΔP = Pressure drop, psid
FPBOV = Fuel preburner oxid valve
OPBOV = Oxid preburner oxid valve
MFV = Main fuel valve
MOV = Main oxidizer valve

S.L. Thrust (lbf)	**= 550,000**
Vacuum Thrust (lbf)	**= 656,000**
S.L. Isp (sec)	**= 379**
Vacuum Isp (sec)	**= 452**
Main Pc (psia)	**= 2,800**

Courtesy Dr. Dianne Deturris, CalPoly U. &
Boeing Co., Rocketdyne Division

Sample Full Expander Cycle Engine Balance

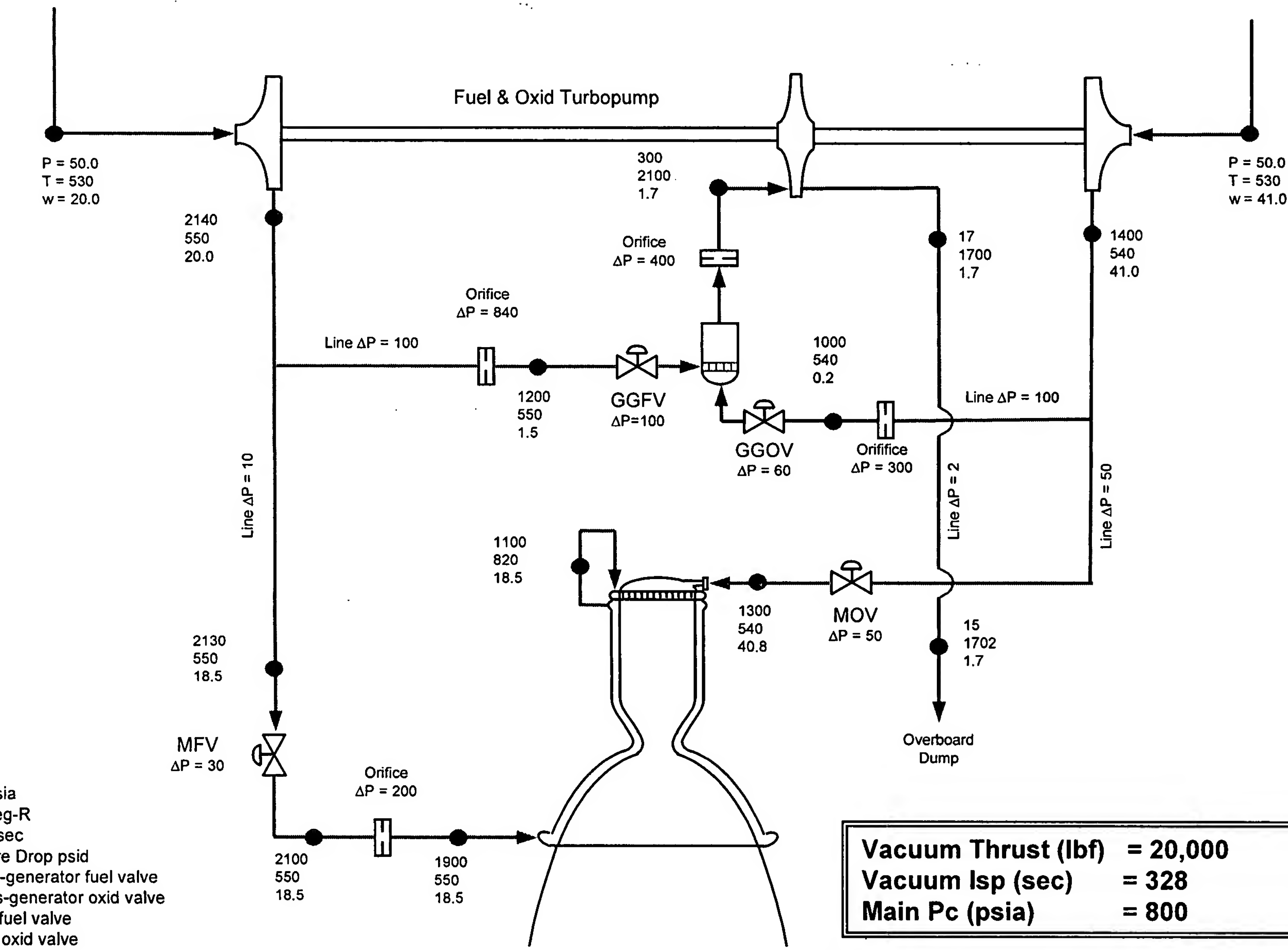


P = Press, psia
T = Temp, deg-R
w = Flow, lb/sec
ΔP = Pressure drop. psid
CCV = Coolant control valve
MFV = Main fuel valve
MOV = Main oxid valve
OTBV = Oxid turbine bypass valve
TBV = Turbine bypass valve

S.L. Thrust (lbf)	**= 239,000**
Vacuum Thrust (lbf)	**= 350,000**
S.L. Isp (sec)	**= 312**
Vacuum Isp (sec)	**= 456**
Main Pc (psia)	**= 1,600**

Courtesy Dr. Dianne Deturris, CalPoly U. &
Boeing Co., Rocketdyne Division

Sample Gas Generator Cycle Engine Balance

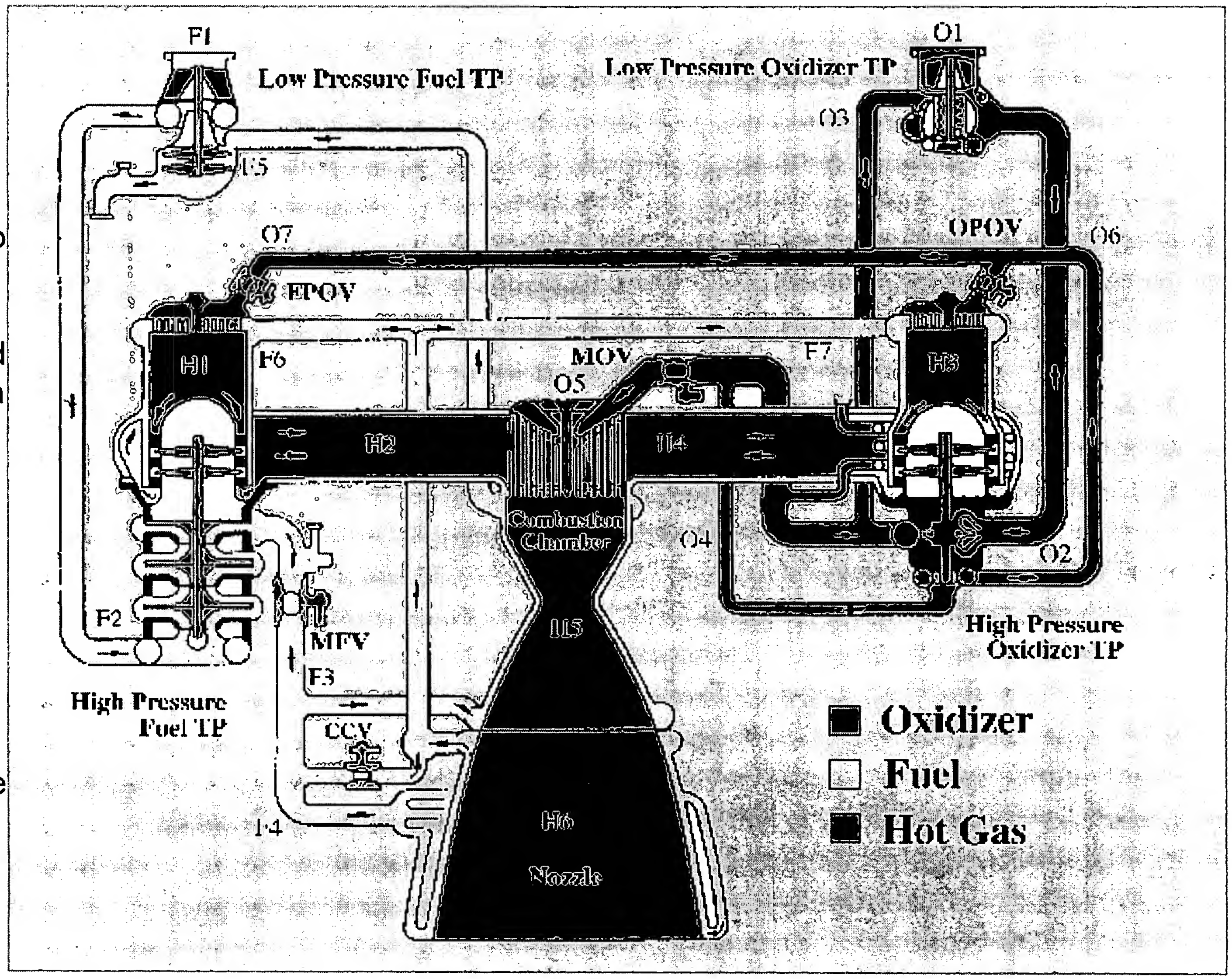


P = Press, psia
T = Temp, deg-R
w = Flow, lb/sec
ΔP = Pressure Drop psid
GGFV = Gas-generator fuel valve
GGOV = Gas-generator oxid valve
MFV = Main fuel valve
MOV = Main oxid valve

Vacuum Thrust (lbf)	**= 20,000**
Vacuum Isp (sec)	**= 328**
Main Pc (psia)	**= 800**

Courtesy Dr. Dianne Deturris, CalPoly U. &
Boeing Co., Rocketdyne Division

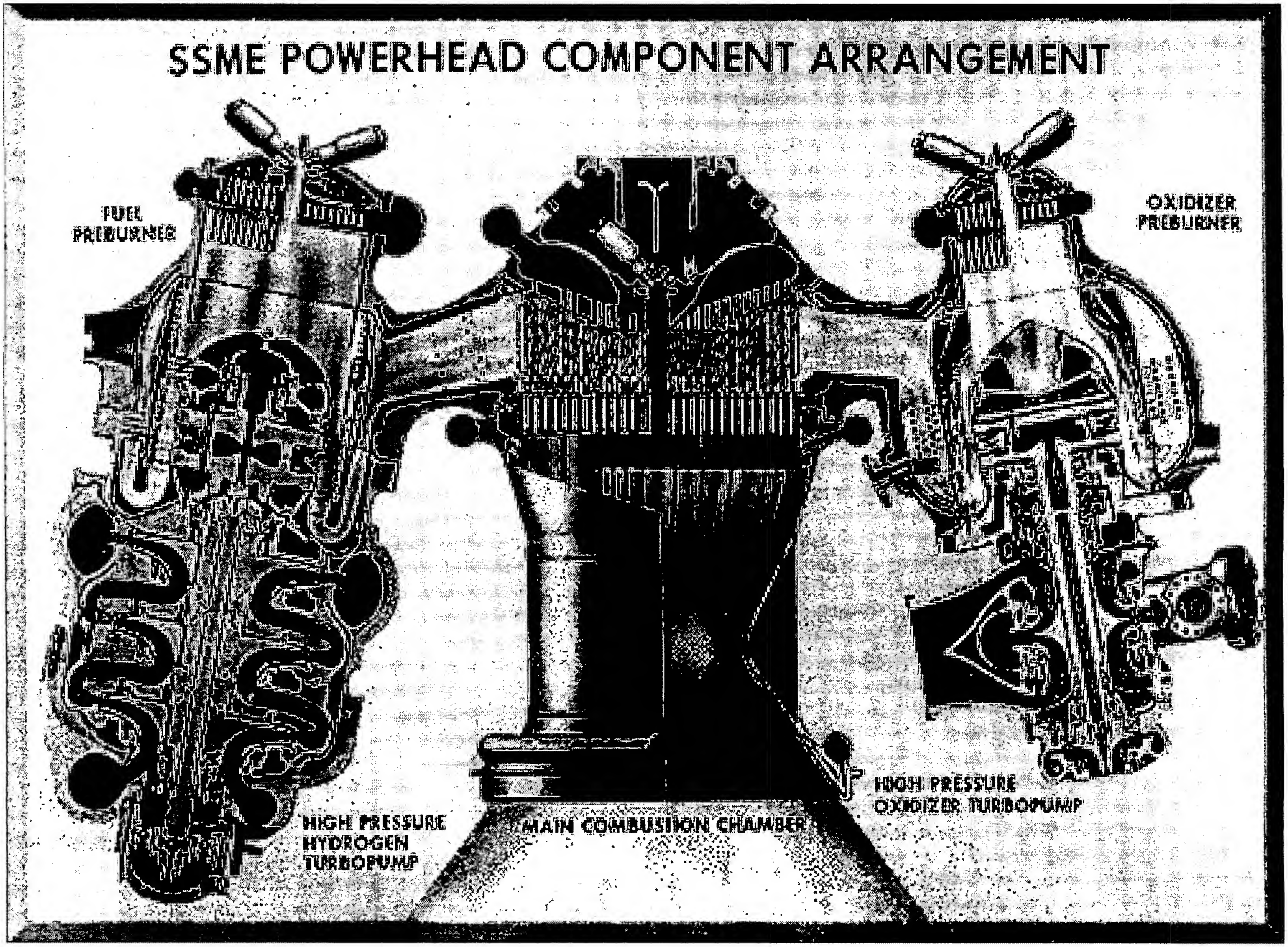
“The Space Shuttle Main Engine (SSME) has 4 turbopumps, 2 low-pressure and 2 high-pressure, each pair is used to force liquid hydrogen and oxygen into the main combustion chamber, where propellants are mixed and burned. With the help of a nozzle, which is regeneratively cooled using liquid hydrogen, thrust is produced after the hot gases are expanded and accelerated. Each high-pressure pump has a preburner, where all the fuel and some oxygen are burned, the gases produced are used to run two-staged turbines that move the pumps' impellers.”



http://web.mit.edu/plozano/www/picts/ssme.gif

In general, closed cycles like staged-combustion or expander will have higher I_{sp} than GG or tap-off (open cycles). However, cost, pressure and complexity are all more.

Examples:
RD-180 / Atlas III
SSME .



http://elifritz.members.atlantic.net/photos/ssme3.gif

Example LOX/RP GG Engine

Mixture Ratio

Main Chamber $\frac{O}{F} = \frac{1941 lbm/s}{827 lbm/s} = 2.35$

Gas Generator (much lower – better to drive turbine) $\frac{O}{F} = \frac{27 lbm/s}{65 lbm/s} = 0.415$

Overall or "tanked" $\frac{O}{F} = \frac{1971 lbm/s}{892 lbm/s} = 2.21$

The net I_{sp} must be calculated from the main and GG mass flows.

Isp (main chamber)

$$= \frac{747000 lbf}{32.2 ft/s^2 \left[\frac{1}{32.2 lbm}\right][1941 lbm/s + 827 lbm/s]}$$

$$= 269.9 \sec$$ **(at sea-level)**

I_{SP} (Gas Generator)

$$= \frac{3000 lbf}{32.2 ft/s^2 \left[\frac{1}{32.2 lbm}\right][27 lbm/s + 65 lbm/s]}$$

$$= 32.6 \sec$$ **(at sea-level)**

As a result, the overall I_{sp} is less than just the nozzle portion.

Overall I_{sp} $= \dfrac{747000 lbf + 3000 lbf}{32.2 ft/s^2 \left[\dfrac{slugs}{32.2 lbm}\right]\left[\left([1941 + 827 + 27 + 65]\right) lbm/s\right]}$

$I_{sp} = 262.2 \sec$ **(net at sea-level)**

$\dfrac{Isp}{Isp_{mainChamber}} \doteq \dfrac{262.2}{269.9} = 97.2\%$ **(staged combustion doesn't have this effect)**

Predicting Engine Pressures

For a typical engine, the system pressures are much higher than the chamber pressure, P_c. Humble gives some rules of thumb for determining pressures.

Open Cycles (like GG) $\Delta P_{dyn} = \frac{1}{2}\rho V^2$

$\Delta p_{lines} \approx 0.35 \sim 0.5 atm$ **Depending on line diameter & length**

$\left(\frac{P_{IN}}{P_{OUT}}\right)_{turbine} \approx 20$

$\Delta p_{regencooling} \approx .15 P_c$ **if regenerative cooled in fuel side.**

$\Delta P_{inj} \approx .2 P_c$ **Injector losses**

$\Delta P_{inj} \approx .3 P_c$ **Injector losses for throttled engine**

Example

For the LH_2 side of a P_c = 100 atm GG engine (unthrottled, regen cooled)

$$P_{pump-exit} = P_c + \Delta P_{inj} + \Delta P_{cool} + \Delta P_{lines}$$

$$P_{pump-exit} = 100atm + 20atm + 15atm + 0.35atm$$

$$P_{pump-exit} = 135.35atm$$

Assume the tank pressure is 3 atm, and V=10m/s.

$$P_{pump-inlet} = P_{tank} - \Delta P_{dyn} - \Delta P_{lines}$$

$$\Delta P_{dyn} = \left(\frac{1}{2}\left(71kg/m^3\right)\left(10m/s\right)^2\right) = 0.035atm$$

$\Delta p_{lines} = 0.5atm$ **(depends on vehicle acceleration and tank height)**

$P_{pump-inlet} = 2.47atm$ **When this falls too low, we need a boost pump.**

$$\Delta P_{pump} = 135.35atm - 2.47atm = 132.885atm = 13.46MPa$$

(within the range of a 1 stage pump for LH_2.)

The pressure "head", H is

$$H = \frac{\Delta P}{\rho g_0} = \frac{132.885\left(101325\frac{P_a}{atm}\right)}{\left(71\frac{kg}{m^3}\right)\left(9.81\frac{m}{s^2}\right)} \approx 19331.5m = 19.33km$$

The same calculation can be performed on the LOX side of this cycle.

Note: Here the turbine is outside the main thrust chamber- the GG operates at a lower pressure.
The object of the turbine is to extract this energy from the flow.

$$P_{t-ratio} = \frac{P_{t-in}}{P_{t-out}} \approx 20$$

Closed-Cycle Engine

For a closed-cycle like staged-combustion or expander, we cannot tolerate this type of pressure loss in the turbine because it is in series with the chamber. The fuel from the fuel pump goes through the nozzle cooling tubes, gets vaporized. Most of it enters the injector and then the combustion chamber. The rest enters the preburner where it mixes with part of the oxidizer and reacts. The exhaust then drives the two turbines before entering the combustor.

For this turbine arrangement (series)

$$\Delta P_{t-series} = \left(P_{in} - P_{out}\right)_{fuel} - \left(P_{in} - P_{out}\right)_{0x} = P_{in\,fuel} - P_{out\,0x}$$

For a closed cycle, we'd like to have

$$P_{t-ratio} = \frac{P_{in}}{P_{out}} \approx 1.5$$ **(otherwise pressures are too high in pump)**

So, for the fuel side

$$P_{pump-exit} = P_c + \Delta P_{inj_1} + \Delta P_{turbine} + \Delta P_{inj_2} + \Delta P_{cool} + \Delta P_{lines}$$

and $$P_{pump-inlet} = P_{\tan k} - \Delta P_{dyn} - \Delta P_{lines}$$

SSME Pressure Analysis Example

Pc ~ 206 atm. Throttleable, staged combustion with regenerative cooling.

Fuel side: $$P_{turbine-exit} = P_c + \Delta P_{inj} + \Delta P_{lines}$$

$$= 206 + 61.8 + 0.2 = 268 atm$$

Assuming injector drop of 0.3 Pc

Use

$$P_{t-ratio} = \frac{P_{in}}{P_{out}} \approx 1.5$$

Then pressure at turbine inlet = 402atm.

$$P_{pump-exit} = \Delta P_{inj2} + \Delta P_{cool} + \Delta P_{lines} + P_{turbine-inlet}$$

$$P_{pump-exit} = 0.2P_c + 0.15P_c + \Delta P_{lines} + P_{turbine-inlet}$$

$$P_{pump-exit} = 41.2 + 30.9 + 0.4 + 402 = 474.5 atm$$

Assume that the pump inlet pressure = 3atm

$$\Delta P = 471.5 atm = 47.8 MPa$$

The corresponding pressure "head", H is

$$H = \frac{\Delta P}{\rho g_0} = \frac{47.8E6}{(71)(9.81)}$$

$$H = 68.6km$$

This magnitude of pressure head requires a 2- or 3-stage pump.

<u>Power Balance</u>

In order to drive the pumps, we must extract work from the turbines.

$$Power = \frac{g_0 H \dot{m}_{pump}}{\eta_p} \quad \text{watts}$$

Note: 1 HP = 550 ft-lb/s = 745.7Watts

Y Naruo, Y Inatani, Y Morita, S Nakai & H Mori, July 15-18, 1997, "Throttling Dynamic Response of LH2 Rocket Engine for Vertical Landing Rocket Vehicle", Presented at the 7th International Space Conference of Pacific Basin Societies (ISCOPS?, formerly PISSTA), July 15-18, 1997, Nagasaki, JAPAN. Paper No. AAS 97-421. Also downloadable from
http://www.spacefuture.com/archive/throttling_dynamic_response_of_lh2_rocket_engine_for_vertical_landing_rocket_vehicle.shtml

Bibliographic Index References and Referring Papers Printable Version

Presented at the 7th International Space Conference of Pacific Basin Societies (ISCOPS?, formerly PISSTA), July 15-18, 1997, Nagasaki, JAPAN. Paper No. AAS 97-421

THROTTLING DYNAMIC RESPONSE OF LH2 ROCKET ENGINE FOR VERTICAL LANDING ROCKET VEHICLE

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Differential throttling of rocket engines for a high performance vehicle such as rocket powered SSTO is studied. For both powered ascent and landing of a vertical landing rocket vehicle, taking into account the attitude motion of the vehicle in atmospheric flight, the necessary restoring moments are evaluated. These were converted to the throttling requirement for each engine in terms of both static and dynamic characteristics, and rocket firing tests were carried out. Engine throttling was done by control of the hot turbine working fluid. Stable static throttling capability was demonstrated from 30 % to 100 % of its maximum thrust level. The frequency response of the engine thrust modulation was investigated and the correspondence between the simulation-model derived dynamic response and the real behavior was verified. Finally closed-loop engine thrust control by connecting a pressure signal from the engine combustion chamber to the throttling valve was tested for better dynamic response. The expected improvement was achieved in the frequency range concerned. As a result of the study, good controllability for attitude control by applying differential thrust of the primary propulsion was demonstrated.

INTRODUCTION

Many system concepts and ideas for fully reusable space transportation systems have been proposed, and technology maturation studies are actively underway. A rocket SSTO (Single Stage To Orbit) should be a final goal of rocket engineers, and it is believed that it has become possible by applying the latest technologies such as engine performance augmentation by external expansion and light-weight materials and structure. Among these system configurations, a vertical lander is one of the attractive systems. There are typically two system configurations from the return flight point of view: horizontal landers and vertical landers. A horizontal lander returns to an air-strip like the Space Shuttle orbiter, which has a wing for landing and after landing it has to be converted to a vertical position for the next launch. On the other hand a vertical lander must have a certain amount of fuel for the landing delta-V, however the wing can be eliminated. For volume and structural efficiency, a vertical lander would be advantageous if properly designed, because it could employ a fatter shape than horizontal landers. This will lead to light-weight construction which is a major concern in designing an SSTO vehicle. From the ground operation point of view, what is needed for such a future vehicle is quick turnaround capability for good reusability like conventional aircraft. To eliminate

huge ground support facilities and laborious ground operations for converting its position from horizontal to vertical would be beneficial for good reusability. But it is still controversial which approach is better in these respects, since no real operational vehicle has ever existed.

Taking a vertical landing vehicle into consideration, it should have a wide range of engine throttling capability for the powered landing maneuver. In some engine and nozzle arrangements such as an external expansion mechanism like an aero-spike engine1, it would not be possible to use engine gimballing because of the fixed engine / nozzle layout. When the primary propulsion is used for attitude control as is done in conventional rocket vehicles by gimballing, the possibility of using differential throttling of these engines for the attitude control moment generator will arise. Even for horizontal landers when they employ such an engine layout, these requests could be common for the high-performance future reusable vehicles. For example X-33; a rocket SSTO demonstrator, employs the linear aero-spike engine layout. Particularly for vertical landers, aerodynamic control surfaces cannot be used at landing, because its air-speed is very low. Therefore, it is important to know the feasibility of differential throttling from the viewpoint of both static and dynamic engine responses for these reasons.

Figure 1 shows a small vertical landing reusable rocket vehicle proposed for demonstrating good operability and reusability2. It is designed so as to return to the launch site after a ballistic flight, and to be used as a test bed for technology demonstration for SSTO such as light-weight construction and high performance propulsion. Another goal of the vehicle is first to achieve a reusable vehicle with enhanced operability, to demonstrate the benefits of reusability. At the same time, the rocket vehicle is used as a multi-purpose sounding rocket. Enhancing the flight operability and low cost operation of the vehicle will give a good opportunity, which means the frequent use of the vehicle is expected. This is the background idea for the present vehicle.

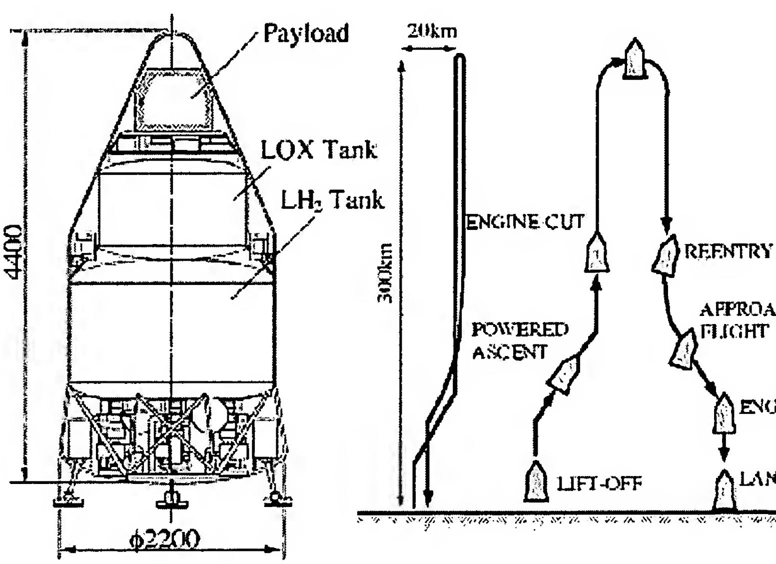

Figure 1: Vertical Landing Reusable Sounding Rocket

As for the performance of the vehicle, it has a ballistic flight capability to an altitude of up to 300 km, and returns safely to the launch site. Finally it lands vertically and offers safe return of the payload. Its propulsion system is composed of four liquid hydrogen / liquid oxygen engines, and it lifts off vertically as a conventional rocket, ascending up to the maximum altitude. After falling back to the atmosphere, it is aerodynamically decelerated and lands vertically at the same place from which it was launched. It uses all four engines for ascent, but it uses two in symmetrically opposite positions for landing by throttling down to about 30% of full thrust level. In the case of one-engine failure, it has the ability to abort and come back to the launch site in the same way as in normal operation. At any time during powered flight, it is able to change to the abort mode in which all engines are cut, and after coasting flight it lands by use of a pair of sound engines in the symmetric position. In that way it has a full-time abort capability and savability in that failure mode. In addition, due to the benefit of deep throttling capabilities of each engine, it has flexible maneuverability in flight; e.g. hovering at constant altitude, low-speed powered flight, and so on.

A major objective of the present study is to identify to what extent the concept of differential

throttling is feasible. Therefore for a case study, taking into account the attitude motion in atmospheric flight of the demonstrator vehicle presented above, the necessary restoring moment is evaluated for both powered ascent and landing. Then this is converted to the throttling requirement for each engine both in terms of static and dynamic characteristics. A rocket firing test was then carried out. Engine throttling was done by controlling the hot turbine working fluid with electric motor driven valve. An attempt to augment the frequency response by giving a combustion pressure signal feedback to the throttling device was made. After showing the results and comparing them with the dynamic model-derived responses, a discussion on further improvement for better dynamic response is made in the following sections.

EVALUATION OF ATTITUDE MOTION AND THROTTLING REQUIREMENT

The vehicle presented above has three phases of powered flight, powered ascent, powered descent before landing, and vertical landing. Differential throttling is done as shown in Figure 2, which summarizes the flight environment and necessary vehicle parameters for the following evaluation both for powered ascent at its maximum dynamic pressure, and for the descent flight transient starting from aerodynamically equilibrium descent to hovering at a certain altitude2. At the final landing the attitude motion would be primarily governed by the soft-landing guidance requirement, not by aerodynamic forces, because the air-speed is very small at landing. In the following part of this section, a simple evaluation is made to give a preliminary requirement for the engine throttling.

	Powered Ascent	Powered Descent
Weight(kg)	3000	1500
Moment of Inertia(kgm^2)	3000	1500
Reference Area(m^2)	4.5	<---
Distance between Engines(m)	1.6	<---
Aerodynamic Static Margin(%)	-10(maximum)	<---
$C_{n\alpha}$(Normal Force Slope;1/rad)	1.5	<---
Velocity(m/sec)	2000	70 to 0
Altitude(km)	20	2 to 0
Thrust per engine(kg)	1700	800

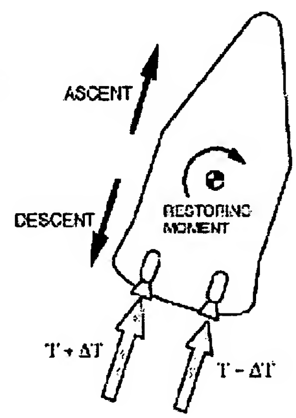

Figure 2: Flight Environment and Vehicle Parameters at Ascent and Descent

Powered Ascent Phase

The necessary range of the engine throttling is derived from the dynamic balance between control moment and aerodynamic torque at maximum dynamic pressure. The dominant disturbance in the atmospheric powered flight is taken into account. Table 1 indicates the required magnitude of throttling as a percentage of the nominal thrust, which is evaluated for the maximum dynamic pressure expected during the powered ascent phase as shown in Figure 2. In the table, the vehicle is assumed to be aerodynamically unstable and the throttling amplitude for three different negative static margins are evaluated. The maximum allowable angle of attack, having a significant influence on the level of disturbance, is also treated as an important design parameter. As maximum angle of attack encountered in this specific flight condition, two cases are taken into account.

The table clearly shows the importance of aerodynamic design of the vehicle, indicating that control design should proceed in conjunction with it. One example of practical requirements for the throttling range may be 20 % for a vehicle having static margin of -5 %. The angle of attack at maximum dynamic pressure is also strictly required to be below 3 degrees. This can deteriorate by inevitable wind profile dispersion, but the level is considered within a scope of

expectation. It should, however, be recognized that a 3 degree angle of attack is equivalent to a deviation of as little as 18 m/s, which is 26 % of the nominal wind velocity at the altitude considered here.

Table 1

NECESSARY THROTTLING AMPLITUDE(%) W.R.T. STATIC MARGIN OF THE VEHICLE

	Xsm (%)		
Angle of Attack(deg)	-5	-7.5	-10
3	16	24	32
5	26	38	52

On the other hand, the required frequency characteristics of the engine throttling can be determined by the tolerable level of delay in the actuating system as evaluated at the rigid mode frequency. At the maximum dynamic pressure, the rigid mode frequency is estimated at 3.6 rad/sec. Allowing a phase delay of 30 degrees, equivalent to 145 msec. delay in time, the bandwidth requirement of the engine throttling control results in approximately 2 Hz, as measured when the phase delay reaches 90 degrees. It must be emphasized here that the delay may not be as short as it should be, although the level is expected to be improved by appropriate control architecture.

Powered Descent Phase

The powered descent phase takes place at an altitude below 2 km, where the aerodynamic forces due to crosswind would be dominant. In this region, the required throttling magnitude can be given as follows

$$\Delta T = 1.43 \rho S_{ref} X_{sm} V_w^{2} / Lc \; < \; 223\text{kgf} \, (13.1\%) \;\; (V_w < 15\text{m/sec}),$$

where Vw means the cross wind speed. Dispersion of the surface wind velocity can be assumed to be below 15 m/sec based on statistical data of normal rocket launch, thus 15 % of the throttling range is required for the descent phase. It should be noted that the requirement for the descent mode is less than that for the powered ascent phase presented above.

Final Landing Phase

As the control system is expected to be utilized in the proximity of minimum control force in the final landing phase, a control system having a linear control characteristic can be treated as an on-off control system. To form a stable limit cycle, the following relation should be satisfied;

$$1 < K < \Delta + 0.5 + \sqrt{\Delta^2 - \Delta} \;\; ; \; K = k/T_d, \;\; \Delta = D/\alpha\, T_d^2$$

where D designates the control dead band, k indicates the rate adding ratio, a represents the control angular acceleration, and Td denotes the total delay time of the control system. It can be practical to take the entire delay to be 200 msec, approximately 50 msec margin against the delay in throttling control. The magnitude of the dead band will be influenced by, for example, the design of the landing gear, but it is left for future consideration. Allowing it to be 2 degrees provisionally, with typical adding ratio of 0.5 sec, yields a requirement for the minimum throttling level of approximately 4 % of the nominal thrust.

From the consideration of these three flight phases, the requirement for the engine throttling control can be summarized as: a throttling amplitude of 4 to 20 % of nominal thrust is necessary, and a concerned frequency response is important at about 2 Hz of the bandwidth. This should be the set of requirements for the following engine response studies, as long as this size and flight-path for the present vehicle are concerned.

ENGINE FOR TEST AND MODELING OF DYNAMIC RESPONSE

Engine as a Dynamic Throttling Test Bed

The rocket engine used for the study is a small liquid hydrogen fueled engine with 1000 kg maximum thrust, which was originally designed and developed for a cryogenic upper stage3. Although this engine is not exactly identical to that assumed in the reusable rocket in the previous section, it is a good test-bed for the present study. The engine has a separate turbopump for each propellant, and employs Expander Cycle. The liquid hydrogen turbopump consists of a two-stage centrifugal pump with shroud and a two-stage reaction turbine. The liquid oxygen turbopump has a single-stage centrifugal pump with shroud and a single- stage impulse turbine. Maximum design chamber pressure is 3.8 MPa and the design MR (oxidizer/fuel mixture ratio) was 5.5. However, we adjusted the rated power level to 2.9 MPa chamber pressure by changing the flow restriction orifices and conducted the thrust throttling tests. The propellant flow schematic of the engine is shown in Figure 3. Figure 4 shows the engine configuration. The engine was set in the ground test facility horizontally. Engine start was done by main propellant tank-head, and the tank pressure was kept around 0.5 MPa for the liquid hydrogen tank and 0.4 MPa for the liquid oxygen tank in order to avoid influences caused by turbopump suction-performance problems during throttling tests. All the tests were conducted under sea level conditions. The ground test facility used for tests is a multi-purpose cryogenic test stand, which has sufficient capability for the range of this test series and for repeatable testing.

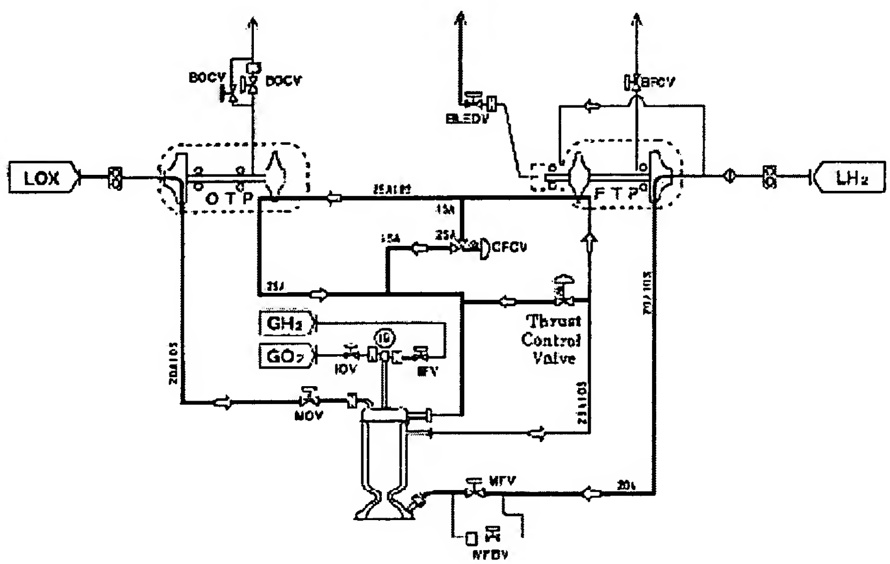

Figure 3: Engine Block Diagram and Throttling Valve

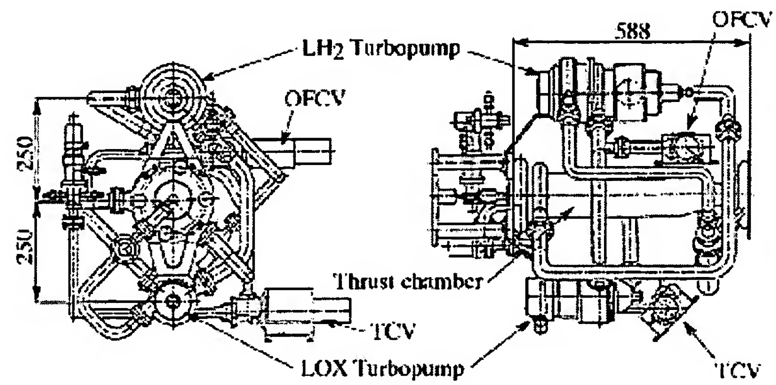

Figure 4: Outer View of the Engine

Throttling Device

In order to change the thrust, two electrically driven valves were installed in the engine feed lines as shown in Figure 3. One is a thrust control valve (TCV), that has a function to by-pass the turbine working fluid out of both turbines. The other is an oxidizer/fuel mixture ratio control valve (OFCV) which will change the mixture ratio to the selected point. However in this test series, it is used only for the duration of the start-up transient. As a result, the oxidizer/fuel mixture ratio is influenced by the TCV actuation in the test for throttling response, which was in the predicted operating range. Liquid-line throttling could be more attractive from the standpoint of rapid thrust response, but it would increase pump discharge pressure during throttling and could create flow coefficient problems at the hydrogen pump. To augment the flow, hydrogen can be recirculated around the pump, but the ramifications of hydrogen recirculation might lead to a temperature rise of hydrogen and pump suction-performance problems. So we adopted a hot-gas side control system for thrust throttling in the present study.

The two valves were identical and had the same actuators and servo controllers. The actuators were to adjust the valve stroke and were manipulated by a rapid response AC driven motor. The servo system was constructed using a PC-based controller and servo driver for the AC motor. To obtain the valve opening stroke, a linear position sensor is attached to the valve poppet and a resolver attached to the AC motor rotational shaft. The PID servo gains of these actuators are tunable by the PC-based controller. However, PD control was employed in the present test. The valve specification is listed in Table 2. A angle-type valve was used for both valves to reduce the pressure drop. In order to control the engine thrust linearly with respect to the valve opening ratio, a linear flow characteristic was selected for both valves. In the closed-loop throttling test in the following sections, the combustion chamber pressure signal, which is proportional to the engine thrust, was used as a feedback signal. Before the testing, the signal noise level was carefully measured and a low-pass filter logic was installed in the PC-based controller. A block diagram of the closed-loop control system is shown in Figure 5.

Table 2

THROTTLING VALVE SPECIFICATION

		TCV	OFCV
Working fluid		hydrogen gas	hydrogen gas
Operating temperature	K	70-473	70-473
Operating pressure	MPa	9.0	9.0
Control valve flow characteristics		liner	modified liner
Cv (Maximum)		5.3	10.5
Valve stroke	mm	10.0	10.0

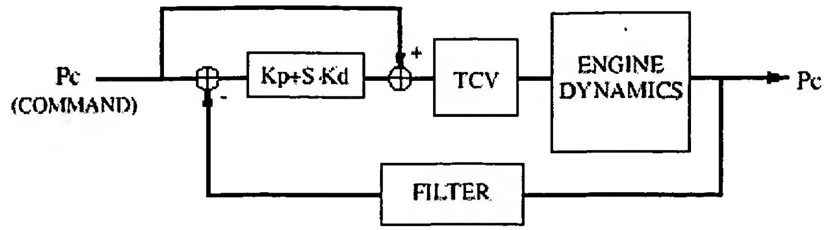

Figure 5: Block Diagram of Closed-Loop Throttling Augmentation

Dynamic Modeling

A dynamic simulation model to evaluate the response of the engine before and after the test was constructed. Generally this type of engine system has some kinds of non-linearity, caused by turbo pump characteristics and hydrodynamic characteristics. So as to make an accurate estimate of the system behavior, a non-linear modeling of the engine dynamics is needed. A numerical simulation code was developed in accordance with the real engine plant shown in Figure 3. Many cases of simulations were executed to make sure to avoid singularities and/or any kind of oscillation before the hot run of the engine.

There is no room to describe the details of the modeling here. However after each test run, some of the specific parameters affecting the whole system characteristics were tuned for some uncertain parameters, and correlated to the previously estimated values, such as the line resistance to the fluid motion, the pump characteristics, the turbine efficiency, the turbo pump inertia and so on. This repeated correction leads to the result in which these uncertain parameters converge to certain values. Before executing the series of closed-loop tests, the prediction of the next test gives quite a good estimate of the dynamic behavior, and determination of the feedback gain was made after careful inspection of these estimates. An example of the correlation between the estimate and the real response is shown in Figure 6 which shows part of the time history of the step-response of the combustion chamber pressure to the engine throttling.

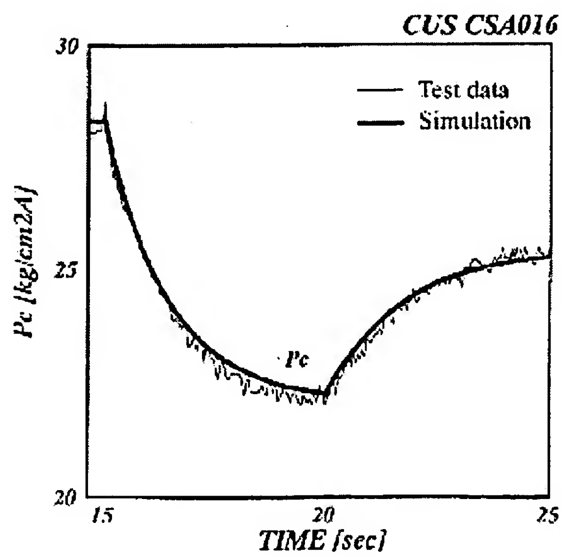

Figure 6: Comparison of Model-Derived Step Response and Test Result

FIRING TEST AND RESULTS

Taking into account the results of the evaluated attitude motion and the resulting throttling requirement for the engine response, a series of ground firing tests was carried out using the engine described above. According to the throttling requirement, the parameters of the firing test were selected as 100 to 40 % of its maximum thrust and 0.5 to 2 Hz frequency range at 10 to 20 % of dynamic throttling amplitude. After confirming the static throttling characteristics in the preliminary firing tests, the open-loop step response and frequency response were investigated. Figure 7 presents the result of static throttling test in which the relation between the valve stroke and the combustion pressure is identified.

Next, tests were performed to investigate the improvement of the dynamic response by adding a feedback loop from the combustion chamber pressure signal to the thrust control valve, as presented in the previous section. A typical example of the time history of the dynamic tests is presented in Figure 8 where the frequency responses are investigated for the two parameters of throttling level and frequency in a single test run. It is clearly observed that the engine responds according to the command signal for throttling. Table 3 shows the summary of the test parameters of the engine throttling. The maximum firing time is about 1 minute in these test runs.

Table 3

SUMMARY OF DYNAMIC FIRING TEST PARAMETERS

Test No.	Feed back	Throttling level(%) and Frequency
CSA 012	-	100-60-80(step)-80±20(1Hz)
014	-	100-60-80(step)-80±20(1Hz)
015	-	100-60-80(step)-80±20(2Hz)
016	-	90-70-80(step)-80±10(1Hz)
018	-	80±10(0.5Hz,2Hz)
019	-	90-40-50(step)-50±10(0.5Hz,2Hz)
020	Kp=0.8,Kd=0.01	90-70-80(step)-80±10(1Hz)
021	Kp=0.8,Kd=0.01	80±10(0.5Hz, 2Hz)
022	Kp=0.8,Kd=0.01	60-40-50(step)-50±10(0.5Hz,2Hz)
023	Kp=2.4,Kd=0.05	60-40-50(step)-50±10(0.5Hz,1Hz)

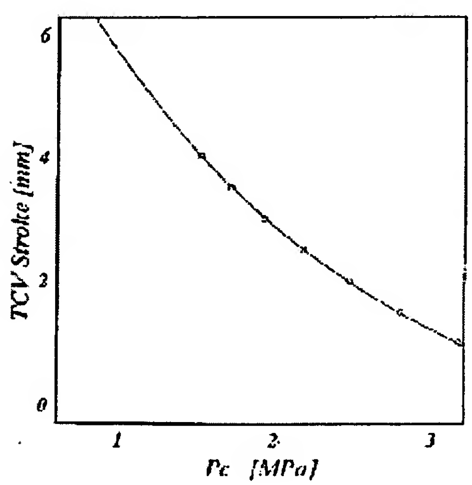

Figure 7: TCV Opening Stroke and Resulting Combustion Chamber Pressure

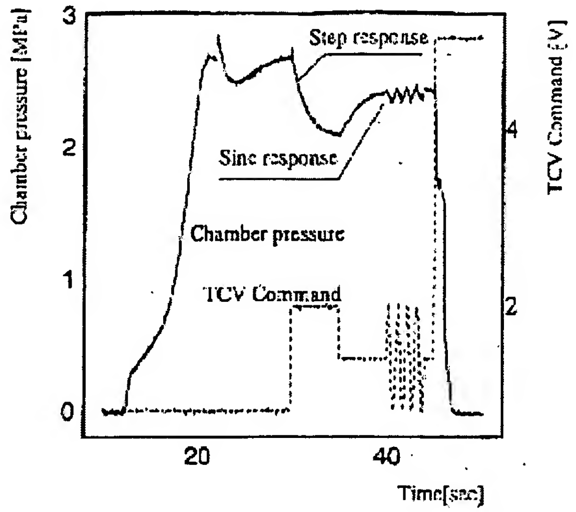

Figure 8:Typical Time History of Dynamic Throttling Test

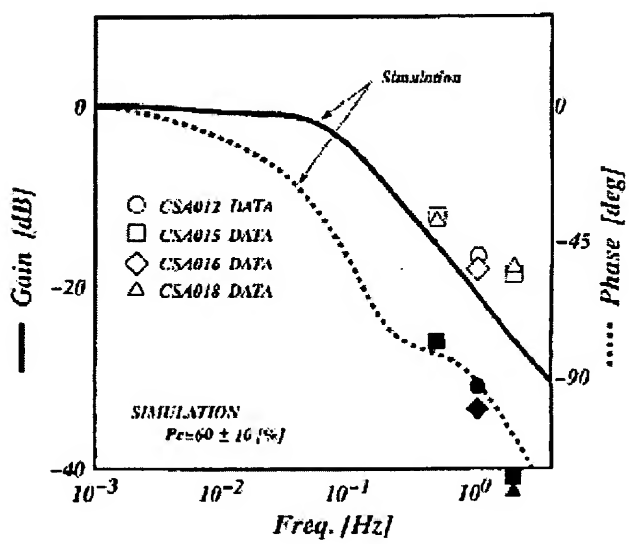

Figure 9:Result of Open-Loop Throttling Test

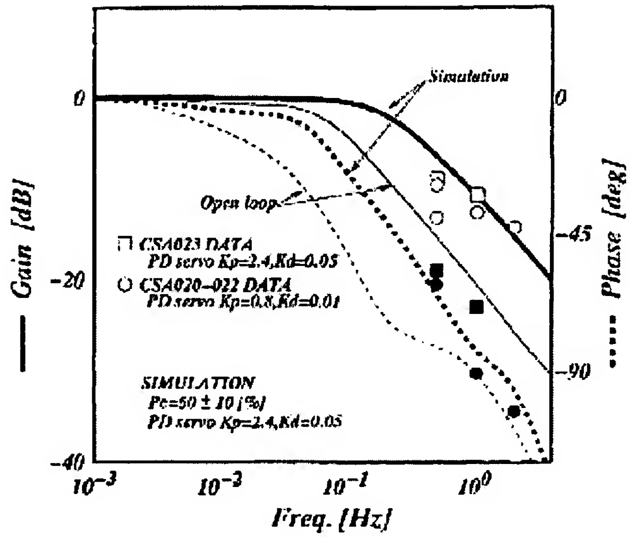

Figure 10:Result of Closed-Loop Throttling Test

Figure 9 presents the resulting open-loop frequency response together with the model-derived characteristics. The resulting phase delay is about 81.5 deg. at 0.5 Hz frequency response, and the response time is over 450 msec. As shown in the figure, the open-loop frequency response at the concerned frequency shows a considerable delay. However, the model-derived responses show fairly good agreement with the results. In addition to these remarks, it is observed that differences in the central thrust level, and the oscillation amplitude do not greatly influence the delay characteristics.

After obtaining the open-loop system response, a pressure feedback closed loop test was conducted to improve the system dynamics for the purpose of meeting the requirements for the vehicle motion. Before executing the test, it was necessary to fix the proportional feedback gain, Kp, and the differential gain, Kd, under the conditions that the chamber pressure must not over-shoot, and the TCV stroke must not saturate due to the current limit for the TCV actuation. As a result, Kp=2.4 and Kd=0.05 were suggested after synthesis of model-derived simulations. However due to safety reasons and limitations of the TCV capability, most of the closed-loop tests were done with gains of Kp=0.8 and Kd=0.01, and the higher gains were used for the final test for evaluating the response at 0.5 and 1.0 Hz frequency as shown in Table 4.

The frequency responses of the closed-loop tests are summarized in Figure 10 where the results both for the lower feedback gains and for the higher gains are presented. The improvement in comparison with the open-loop characteristics is obvious. The phase delay is reduced to 65 deg. and response time is improved to 360 msec at 0.5 Hz frequency with feedback gains of Kp=0.8 and Kd=0.01. Also presented are the improvements with higher-gain feedback.

DISCUSSION AND POSSIBLE IMPROVEMENT FOR BETTER DYNAMIC RESPONSE

As presented in the previous sections, the dynamic throttling characteristics have been identified. Due to the limitations of the number of test runs and the performance of the thrust control valve, the results are not comprehensive. However, the augmentation of the dynamic response was demonstrated, and the model-derived simulation technique satisfactorily worked on every aspect in the testing, such as estimating the response, determining the feed-back gains, and so on. It was also demonstrated that the simulation result is valid even in evaluating closed-loop characteristics, and so further improvement by giving more optimal and higher feedback gains would be possible. Based on the test results, Figure 11 shows the simulated frequency response for the higher gains of Kp=12.0 and Kd=0.3. This would be realized by

giving a much higher current to the TCV and careful selection of feed-back signal filtering parameters, because the higher feedback gain imposes larger noise-sensitiveness.

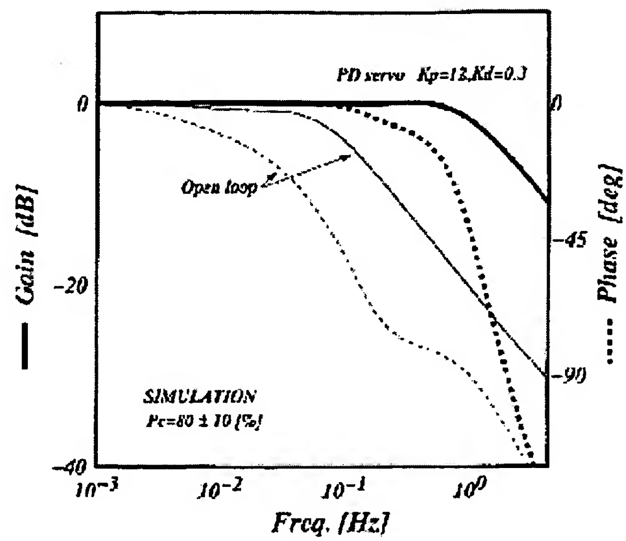

Figure 11: Estimated Higher Gain Response

Table 4 summarizes the test results and the expected improvement by optimal feedback as described. Theoretically, higher gain feed-back makes it possible to improve the phase delay to under 15 deg., and response time to under one fifth of that in the open-loop characteristics. In comparison with the requirement based on the vehicle attitude dynamics, ie. 90 deg. phase delay at 2 Hz frequency as presented in the previous section, this improvement by closed-loop throttling control would be satisfactory. The TCV should have a wider range of stroke and better dynamic response for this purpose. In addition to these augmentation techniques, for the improvement of open-loop characteristics, in other words for a better dynamic response of the engine itself, making the inertia of the turbo pump as small as possible would be essential from the consideration by dynamic modeling.

Table 4

RESULTING AND EXPECTED ENGINE RESPONSE AUGMENTATION AT 0.5HZ AND 2HZ

	Frequency	Closed loop (Hi-Gain)	Closed loop (Test)	Open loop (Test)	
Phase delay (deg)	0.5Hz	-14.5	-65.0	-81.5	
Time(msec)			81	360	455
Phase delay (deg)	2.0Hz	-90.0	-102.7	-128.1	
Time (msec)			125	142	177

CONCLUDING REMARKS

Static and dynamic throttling capability was demonstrated from 40 % to 100 % of the maximum thrust of a liquid hydrogen/liquid oxygen rocket engine. The frequency response of the engine throttling was investigated, and good correspondence between the simulation-model-derived dynamic response and the real behavior was verified. Finally closed-loop engine thrust control by connecting the pressure signal of the engine combustion chamber to the throttling valve for better dynamic response was carried out. By changing the feedback gain, improvement of the frequency response was investigated, and the expected augmentation of the dynamic response was demonstrated in the required frequency range derived from the evaluated attitude motion of the reference vehicle. Based on the present study, good controllability by the application of differential thrust of the primary propulsion system for attitude control would be realistic. The engine dynamic simulation model was also verified, including the closed-loop characteristics,

and the lessons learned from the study give a guide for further improvement including better dynamic characteristics of the engine throttling.

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